AD-A277 398

ENTATION PAGE

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mated to average ... including the time for reviewing ... existing data sources, ... reviewing the ... Send comments regarding this burden estimate or any other aspect of this ... burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson ... Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503

PORT DATE	3. REPORT TYPE AND DATES COVERED
	ANNUAL 01 Feb 92 TO 31 Jul 93

4. TITLE AND SUBTITLE

STEPS TOWARD UNDERSTANDING THE SOLAR DYNAMO

5. FUNDING NUMBERS

61103D
3484/HS
AFOSR-90-0116

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8. PERFORMING ORGANIZATION REPORT NUMBER

AFOSR-TR- 94 0098

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AFOSR/NL
110 Duncan Avenue, Suite B115
Bolling AFB DC 20332-0001

Dr Henry R. Radoski

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

94-09426

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release;
distribution unlimited

Approved for public release;
distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

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14. SUBJECT TERMS	15. NUMBER OF PAGES
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
(U)	(U)	(U)	(UL)

Narrative for Annual Report

AFOSR Grant: AFOSR-90-0116
University of Hawaii/ Barry LaBonte
Period: February 01, 1992 to July 31, 1993

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Annual

[redacted] PROJECT REPORT
AFOSR-90-0116
Steps Toward Understanding the Solar Dynamo

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I. ABSTRACT.

The standard model of the solar dynamo, the mean-field model, has numerous problems. Observational and theoretical tests of a new model of the solar dynamo, the fluxtube model, were needed to determine whether it might replace the standard model. Under this project we have made a variety of tests that show the fluxtube model is better able to explain the observed properties of the magnetic fields on the Sun. During the course of this project, the deep involvement of students in the research and the upgrade of research facilities have improved the University's capabilities for providing technical education.

II. INTRODUCTION

Magnetic fields on the Sun are directly responsible for the time-varying effects of the Sun on the Earth. Explosive release of magnetic energy in the atmosphere of the Sun in flares showers the Earth with high energy radiation and particles and disturbs the Earth's magnetic field, producing aurorae. Disruption of satellites, radio communication, and electrical power grids occur with little or no warning. The appearance and disappearance of dark magnetic sunspots and bright magnetic faculae on the solar surface directly change the radiant light and heat falling on the Earth's atmosphere and surface. Variation of the ozone layer and alteration of the climate are affected by this radiant energy.

The process which produces magnetic fields in the Sun is called the solar dynamo. The dynamo operates inside the Sun, out of view. Traditional efforts to understand the dynamo focused on observations of magnetic fields once they have emerged to the solar surface. Statistics of the amplitudes, directions, and spatial patterns of the magnetic fields led to the phenomenological Babcock-Leighton model: a global poloidal (north-south) field is stretched into a toroidal (east-west) field by differential rotation of the Sun, erupts to the surface, diffuses to the poles and, reverses the sign of the original poloidal field. The dynamo then repeats periodically. Parker and many other workers derived a form of oscillator equation that describes this model analytically, called the mean-field model. It treats the magnetic field as a smooth, weak field distributed over much of the volume of the Sun.

The mean-field model has many problems. On the solar surface, the magnetic fields are strong and concentrated in a small fraction of the area. Mean-field models that mimic the solar behavior are kinematic: the flows of material inside the Sun are postulated *a priori*. Attempts to make self-consistent dynamos in which the flows are calculated along with the magnetic fields fail to reproduce solar behavior. Observations of the flows inside the Sun from analysis of solar oscillations show that the flows have the wrong form to produce the mean-field dynamo.

A new model appeared, based on the observation that magnetic fields at the solar surface are concentrated in small areas, called fluxtubes. The fluxtube dynamo would occupy only a small fraction of the solar volume, just below the solar convection zone. The appearance of fields at the surface would be naturally concentrated if they are produced in that form at depth.

Our tests of the fluxtube model took two forms. First, we developed tools to directly probe the form of magnetic fields below the surface by measuring their interaction with solar acoustic waves (5-minute oscillations). Second, we developed better theoretical understanding of the properties of the fluxtube dynamo to understand how well it matches the solar behavior.

III. PERSONNEL

The scientific personnel who worked on this project include the PI, Co-Investigator Dr. George Fisher, Assistant Astronomers Dr. Douglas Braun and Dr. Edward DeLuca, Astronomer Dr. Andrew McClymont, and graduate research assistants Robert Ronan, Matthew Penn, Yuhong Fan, Brian Patten, Renate Kupke and Kristin Blais.

Technical work was performed by programmer James Anuskiewicz, electronics engineer Mark Waterson, observer Darryl Koon, observatory superintendent Anthony Distacio, research associate Judson Hewitt, and the technicians in the Institute's mechanical and electronic shops.

IV. INTERACTION OF MAGNETIC FIELDS WITH ACOUSTIC WAVES

One of the keys to this project was our earlier discovery that sunspots and faculae absorb a large fraction of the acoustic waves that strike them. Acoustic waves in the Sun are generated by turbulence in the convection that carries heat to the solar surface. The Sun acts as a resonant cavity to select particular combinations of wavelength and frequency that have large acoustic power. Magnetic fields were shown to absorb acoustic waves with wavelengths less than the size of the magnetic structure (sunspot or facular region).

Scattering of waves from obstacles is a powerful tool for determining the nature of the objects. Solar acoustic waves are observed at the surface but travel to great depths inside the Sun, where the magnetic dynamo lies. We have explored various aspects of this wave-field interaction to work toward mapping the fields at depth directly.

A) Acoustic Phase Shifts

Our most important result is that the phase of the interaction can be measured as well as the amplitude. In scattering problems, most of the information is in the phase. D. Braun and collaborators showed that the phase shift caused by the scattering is measurable under

specific conditions. The multitude of resonant modes of the solar waves leads to ambiguity in the phase if individual modes are not isolated. The isolation of modes normally requires observations over durations (days) that are long compared to the evolution time of solar magnetic fields. Braun showed that for carefully chosen observations, durations as short as 10 hours will suffice.

The basic result of the phase shift measurements for acoustic scattering from sunspots is that the phase shift grows monotonically with wavenumber (1/wavelength) and is independent of frequency. Indeed, the phase shift at high frequencies is large while the absorption (amplitude shift) declines to zero. The sense of the phase shift is that the waves travel slower in the spot than in the unmagnetized Sun, implying that the waves are converted to magnetic slow modes.

B) Sunspot - Wave Interaction

A key question in deciding the utility of wave-field interaction for probing magnetic fields is to understand the physics internal to the fluxtube. Sunspots are the only fluxtubes large enough to permit study of their internal structure. As a part of his Ph.D. thesis , M. Penn used a variety of techniques to determine the detailed behavior of sunspot oscillations. He showed that the oscillations internal to sunspots are not self-generated or internally resonant, but are 5-minute waves that have traveled into the sunspots from outside. He further showed that the absorption of acoustic waves by sunspots is not limited to a boundary layer at the outer edge of the spot fluxtube, but is distributed internal to the fluxtube. This work shows that the wave-field interaction does contain information about the internal nature of the fluxtubes as well as their existence.

C) Sunspot Structure at Depth

Scattering of acoustic waves from objects in fluids is a subject with many analogs and extensive laboratory experiments. All of these analogous systems and experimental results demonstrate basic principles of the interaction. First, the wave interaction is nil at long

wavelengths, growing to a maximum for waves which match the size of the object. Multiple objects of the same size in the volume produce higher total absorption, but the spectrum against wavelength is unchanged. Second, if the object is internally smooth, the interaction with the waves shows periodic structure with wavelength, as the incident waves resonate with the internal oscillation modes of the object. Internally structured objects show no resonances, only a flat, high level of absorption.

The absorption of acoustic waves by sunspots and facular regions has been measured for more than a dozen cases. LaBonte examined these cases to determine their relation to the basic principles of wave-object scattering. The spectra of absorption with wavenumber all show smooth behavior, indicative that the magnetic objects are internally structured. In most cases, the absorption spectrum implies a size that is comparable with the size of the sunspot umbra (acoustic size ~1/2 the penumbral size). But in a few cases there are marked differences. The March 1989 sunspot group had an acoustic size corresponding to the size of a single spot umbra, rather than 1/2 the penumbra. This group had the normal form for a large compact group, with many umbras in a single penumbra. The acoustic data show that this fragmentation of the fluxtube persisted below the surface as well. A second disparate result was found in a decaying sunspot. On two successive days the surface spot shrunk in size by a large factor, while the acoustic size remained constant. This indicates that the fluxtube remained large or intact below the surface.

D) High Frequency and High Wavenumber Waves

The acoustic waves most strongly affected by interactions with magnetic fields are those with the highest wavenumbers (high-k). The acoustic waves with the most direct interaction with the solar surface are those with the highest frequencies (high-f). These waves are generally poorly observed in standard oscillation experiments. As part of his Ph.D. thesis, R. Ronan studied the properties of these high-k, high-f waves and their behavior near the time of solar activity maximum. He found several significant differences from past studies that demonstrate new aspects of the solar magnetic activity cycle.

High-f waves are not actually trapped inside the Sun as resonant oscillations. The reflection near the solar surface caused by the steep temperature gradient is reduced at high-f. The existence of modal structure in f-k diagnostic diagrams is caused by a simple 2 path interference, as waves emitted may travel directly out through the surface or may travel downward and be reflected once before exiting the Sun. Ronan extended measurements of the f-k power peaks to higher frequencies (above 10 mHz, or 100 second periods) and to higher wavenumbers (k ~ 400 for the highest detectable modes) than past work by the Kitt Peak group. More important, he found large frequency shifts in these pseudo-modes compared to the Kitt Peak data taken near solar activity minimum. Frequency shifts were tens of microHz. Much smaller frequency shifts (nanoHz) had been seen by the Caltech group in the normal 5 minute oscillations as activity varied. Because the high-f waves sample only the highest layers of the Sun, careful modeling of Ronan's wave frequency shifts will reveal new details of the shallow layer in which most of the solar acoustic power is generated.

Ronan also examined the frequency splitting of normal oscillation modes at the time of activity maximum to determine what internal structure might vary during the solar cycle. He found evidence of a thermal disturbance at intermediate latitudes at depth in the convection zone, by comparison with data from a variety of previous work from times of low activity. Structure of this type could be a signature of distortion of the normal convective flow by the dynamo magnetic fields.

E) Mapping Acoustic Power

The absorption of acoustic power by magnetic fields is large: 10-20% in facular regions, 20-70% in sunspots. Many of the waves that are absorbed by magnetic fields would otherwise travel unaltered completely around the Sun. Braun and Lindsey realized that it might be possible to detect magnetic activity on the unobservable hemisphere of the Sun by searching for acoustic shadows at the antipodes. A simple measurement of the total acoustic power at a given spatial location and a broad wavenumber/frequency band is far easier to make than a full

analysis for measuring the absorption. In separate analyses, Braun and Lindsey, using Kitt Peak data, and LaBonte and Toner, using Hawaii data, searched for such acoustic shadows. No detectable signals were seen, with noise levels in the latter study of ~2%.

These direct maps of acoustic power do reveal important information about the nature of acoustic power near solar magnetic regions. It has been known since the discovery of solar oscillations that their amplitude is reduced in magnetic regions. LaBonte and Toner showed that the decrease in power is identical at low-k and high-k. Because the latter waves are known to be absorbed while the former are not, the decreased total observable power is lower as an effect of a visibility change. The waves traveling in active regions are hidden in some way.

Comparing the trapped (5-minute or 3mHz) waves with the escaping (> 6mHz) waves, LaBonte and Toner found that active regions show excess power at high-f in a fringe just outside the magnetized area. Either excess power is generated around active regions, or wave trapping extends to much higher frequencies in those areas than elsewhere on the Sun.

F) Optimizing Acoustic Observations

Traditional studies of solar oscillations treat the Sun as a single resonant cavity and seek to measure the properties of the resonant waves. Improvements in these studies require long durations of observations to better resolve the average mode properties. By contrast, studies of rapidly evolving magnetic structures require the observations be completed before the structures have changed form. In addition, accurate phase measurements are more demanding of the Nyquist frequency, as waves which are aliased (have frequencies too near the highest measurable in the data) cannot be used. Further, the appearance of activity is unpredictable. We therefore had to develop new techniques for observations.

Our observations are regularly taken with 30 second cadence to raise the Nyquist frequency well above any interesting limit. This compounds the data analysis burden compared to the normal 60, 75, or even 90 second cadence used to study 5-minute oscillations. Our observations also were conducted continuously, on every clear day at

Mees Solar Observatory, Haleakala, to record magnetic activity at all stages of development. This now represents the most extensive archive for oscillation data extant, and will provide the basis for much future work.

The most severe limit of a normal observatory is the day/night cycle. The use of observing networks and observations from the South Pole have shown that data free from the diurnal cycle are better suited for the kind of measurements that we need. We therefore undertook to test a similar but more friendly site, namely the north polar region in Alaska.

Our tests and experience from 2 campaigns of observing in Alaska show that the interior of the state, and in particular the Yukon Flats region, offer many of the advantages of the South Pole and few of the disadvantages. Conditions during the prime observing season of late-April to early-July are temperate rather than life-threatening. Transportation and communication are simple and low cost. The conditions for solar observations are good for our objectives of studying activity, with long hours of sunshine and acceptable sky conditions.

The data needed for acoustic studies of magnetic fields must have sufficient spatial resolution to detect high-k waves at all times. To this end we designed and built a new instrument, the P-mode Oscillation Imager or POI. Similar in concept to the High-l Helioseismometer at Kitt Peak, it uses a large format CCD array (1024x1024), narrow interference filter (4 Angstroms at 3933 Angstroms wavelength) and a fast guider system to observe intensity oscillations in the inner wings of the Ca II K-line. The POI is installed at Mees Solar Observatory and operates daily. A second set of the critical components is used for laboratory development, short lead-time spare parts, and as the core for a second instrument for future observing campaigns.

V. PHYSICS OF THE FLUXTUBE DYNAMO

The idea of the fluxtube dynamo is that magnetic fields throughout the Sun are strong and highly concentrated just as we see them on the surface. The individual fluxtubes then have an identity and can be followed as objects in many cases, rather than as vector fields.

Concepts of discrete, or topological dynamo processes are well known in other areas of magnetohydrodynamics. The idea of the solar fluxtube dynamo is not fully developed, and under this project we made numerous studies of aspects of this model.

A) Fluxtube Dynamics

Because the fluxtube is small and threaded with strong magnetic field, it can be treated in many cases as a line object moving in a 3-dimensional Sun. In a series of papers, Fisher, Fan, DeLuca, Patten and collaborators developed the analytic techniques for following the evolution of fluxtubes in the solar interior. Key additions to the techniques included allowing for aerodynamic drag forces on the fluxtubes from the surrounding medium and treatment of the mass flows internal to the fluxtube.

Turbulent flows in the solar convection zone prevent the growth of ordered magnetic fields that form the basic solar cycle. Observations of the solar rotation as a function of depth and latitude show that the kinds of ordered flows (that is, shear flows) needed occur at the lower boundary of the convection zone. We studied the behavior of fluxtubes as they ascend from the lower boundary to the surface. Fluxtubes that are partially pulled into the convection zone are unstable to ascension because they buoyant; their internal density is lower that the surroundings. The fluxtubes rise quickly enough that thermal equilibrium with the surroundings is not reached. Rise times of order a month are the normal condition for fluxtubes of the correct size to produce normal sunspots. The length of the fluxtube that needs to be perturbed into the convection zone is of order 100 Mm, a size of the same order as that of convective flows near the bottom of the convection zone that might overshoot into the stable layers containing the flux.

As the fluxtubes rise to the surface, drag and coriolis forces affect the motions. Buoyancy is radial; coriolis forces tend to force the tubes to higher latitudes, but drag stalls the latitudinal motions and keeps the fluxtubes at low latitudes. This matches the observed concentration of magnetic eruption at low latitudes.

As the fluxtubes rise the material inside them conserves angular momentum, producing a flow along the ascending portion. Coriolis forces on the flow twists the fluxtube, forcing an initially purely poloidal fluxtube to assume a tilt as it nears the surface. The magnitude and direction of this tilt depends on the properties of the fluxtubes, in particular their magnetic field strength. Magnetic fields on the solar surface are observed to have such tilts, called Joy's Law. To match the observations, field strengths of 30 - 90 kG are required. Fields outside this range have tilts either too large or too small at the surface. This range of field strengths differs among calculations which include different physics. Our more comprehensive approach is at present the best available.

As the fluxtube rises, gravity alters the flow inside it, adding to its magnitude in one leg and subtracting in the other. This difference in flow speed causes differences in the other physical properties of the fluxtube. Most important, the magnetic field strength is larger in the west (preceding) leg by a factor of 2 than in the east (following). This asymmetry between the two sides of the fluxtube perfectly mimics the observed asymmetry of solar magnetic regions. Sunspots on the preceding side of regions are larger and longer lived than those on the following; the latter often never form, leaving only dispersed facular fields. No previous model has addressed this obvious solar phenomenon. The key physics are that the magnetic fields are concentrated in fluxtube form through to the bottom of the convection zone and are anchored at or below that level.

Another aspect of observed surface magnetic fields that has puzzled dynamo modelers has been the apparent absence of tension forces in restricting the motions of fluxtubes across the surface. Fluxtubes act as "corks", responding to the surface gas flows. Our calculations show that as fluxtubes come to the surface, at a depth of only about 20Mm (10% of the convection zone), the pressure balance with the surroundings forces the fluxtube to balloon or fragment. When fields erupt at the surface, they do so as small elements which then move together to form sunspots. For large units of flux such as sunspots, the identity of the tube through this "disconnection" layer would most likely be preserved. But for small units, as in tiny facular fluxtubes, the tension forces holding them to the site of the initial eruption would be low. These small elements could then "diffuse"

across the solar surface, as is observed. This separation of the surface behavior from the appearance at depth is also a unique feature of the fluxtube models.

B) Reconnection in the Solar Interior

The problem of generating magnetic fields in the solar interior also includes the problem of destroying the unwanted fields produced by small-scale turbulence or the residual oppositely directed fields of the previous magnetic cycle. The reconnection of magnetic fields in the solar atmosphere to convert magnetic energy to other forms in flares has been studied in detail. But the opposite case of reconnection in a dense medium, as in the solar dynamo region in the interior, has not been closely examined. DeLuca and collaborators modeled the behavior of reconnection in conditions more appropriate for the dynamo. He found that the reconnection can proceed in a "fast" regime, with reconnection speeds of order the Alfven speed. The existence of fast reconnection is a key to permitting the dynamo fields to evolve without becoming hopelessly tangled. In a fluxtube dynamo, it is assumed that tubes are twisted, folded, stretched as units, then reconnected to neighbors to build the large-scale fields. We now know the reconnection can proceed as needed.

C) Chaotic Field Generation

Flows in the convection zone, and probably in the overshoot region just below it, are chaotic. Two adjacent particles will move apart exponentially fast in the flows. DeLuca examined whether chaotic flows can stretch and thus enhance magnetic fluxtubes. Despite the intuitive notion that chaos is unpredictable, there are known to be well ordered flows that behave chaotically; one most thoroughly studied is the ABC flow, which is periodic in all 3 dimensions. DeLuca modeled an ABC flow with physical parameters appropriate to the solar convection zone and followed the evolution of fluxtubes in it. Very small tubes collapsed under tension forces, but larger tubes were all enhanced, by as much as one order of magnitude in some cases. The ability to manipulate fluxtubes in flows is another key part of the dynamo model.

D) Convection Modeling

Another problem in modeling a fully consistent solar dynamo is the ability to deal correctly with convection. Laboratory experiments with helium in large volumes are beginning to explore conditions of convective turbulence that in some ways match those in stellar interiors (where conditions are much more turbulent than any normal terrestrial convective system). DeLuca and collaborators conducted large-scale numerical experiments to compare with the laboratory cases, and found that they could reproduce numerous details of the convection over approximately 10 orders of magnitude in Reynolds number. They were able to show that breaks in the spectrum of convective power as a function of size scale corresponded to specific transitions in the flow fields, as larger numbers of counter cells and plume flows develop.

E) Acoustic Absorption in Fluxtubes

The mechanism that causes the absorption of acoustic waves in fluxtubes is not known. The best available mechanism is resonant absorption, in which waves are trapped in a thin boundary layer of a fluxtube. The gradient in the physical properties in the boundary layer causes trapping for a wide variety of waves. However, if the fluxtube is internally smooth, the absorption is periodic in wavenumber, as the tube as a whole interacts with the waves. Attempts to eliminate this (unobserved) periodicity succeed only if the fluxtube is internally inhomogeneous.

LaBonte and Ryutova explored an alternate mechanism, based on the principle that the fluxtube is highly inhomogeneous, but on scales much smaller than the size of the tube. As waves pass through such a tube, gradients in the physical properties appear not only on the scale of the wavelength, but also on the scale of the inhomogeneities. Dissipation is much larger in these small-scale gradients, and wave power is absorbed quicker. This mechanism had been studied for heating the solar corona. The calculations were redone for the case of high density as in sunspots below the solar surface. The detailed behavior of the absorption expected from this mechanism matches that of the observed absorption in key ways: no absorption at low wavenumbers and constant, high absorption at high wavenumbers.

Comparing these alternate models for the absorption mechanism and Penn's observational result that the absorption is distributed inside a sunspot, it is clear that the internal structure of the fluxtube is inhomogeneous and probably highly so.

VI. UNIVERSITY EDUCATION

One of the primary goals of the University Research Initiative is to strengthen graduate education. Under this project, graduate students have been fully involved in all parts of the work. The broad approach of this project, integrating instrumentation, observation, data analysis, and theoretical analysis have given these students a unique experience.

Three students completed their Ph.D. theses under this project: Dr. Robert Ronan, Dr. Matthew Penn, and Dr. Yuhong Fan. They actively participated in all phases of the project, including instrument development, observing campaigns, theoretical analyses, data reduction. Drs. Penn and Fan now are postdoctoral fellows at the National Solar Observatory. Dr. Ronan is at the School of Medicine of the University of Massachusetts, working to apply his skills to medical imaging.

Three other graduate students worked as Research Assistants on the project: Brian Patten, Renate Kupke, and Kristin Blais. They, too, contributed to a wide range of project activities. All three are continuing on to their Ph.D.s; Kupke and Blais are using data and instrumentation from this project in their thesis work.

We have already mentioned the new instrumentation available because of this project for future students to use. Besides the instruments themselves, this project made a substantial upgrade of the computing facilities (workstations and their peripherals) which serve the student research needs. Integrated with the facilities provided by NASA's Yohkoh project, these form a worldclass reduction and analysis system.

VII. SUMMARY

Have we learned anything about the solar dynamo? Yes. Our work on fluxtube dynamics have gone far beyond what we originally thought possible in defining the fluxtube dynamo as the model to examine. Other workers at the Institute for Astronomy are beginning to re-examine observations of the surface solar magnetism in terms of fluxtube emergence to determine whether electric currents carried by the fields can tell us more information about the dynamo region. Our development of observational tools and their application to probing the solar magnetic fields at depth have also been unique and are attracting new groups to work in this area.

Has this URI grant enhanced the technical education that we are able to provide to students at the University of Hawaii? Yes. Students now working on their Ph.D. theses are using the facilities and data that this project alone made available, and other students will do so in the future.

The problem of the solar dynamo is not solved. We have taken steps down- new roads toward that solution.

VIII. PUBLICATIONS

The work done under this project has been published in a variety of journals and conference symposia. The following is a list of publications of the scientists involved with the project that were submitted from the Institute for Astronomy. In some cases work was submitted through co-authors' institutions.

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